

# The evolution of galaxy formation

Douglas Scott

University of British Columbia

## Abstract

Our history of understanding galaxy formation could be traced through the development of individual ideas. A cynic might be tempted to suggest that new catchphrases are developed at a faster rate than genuine progress is made.

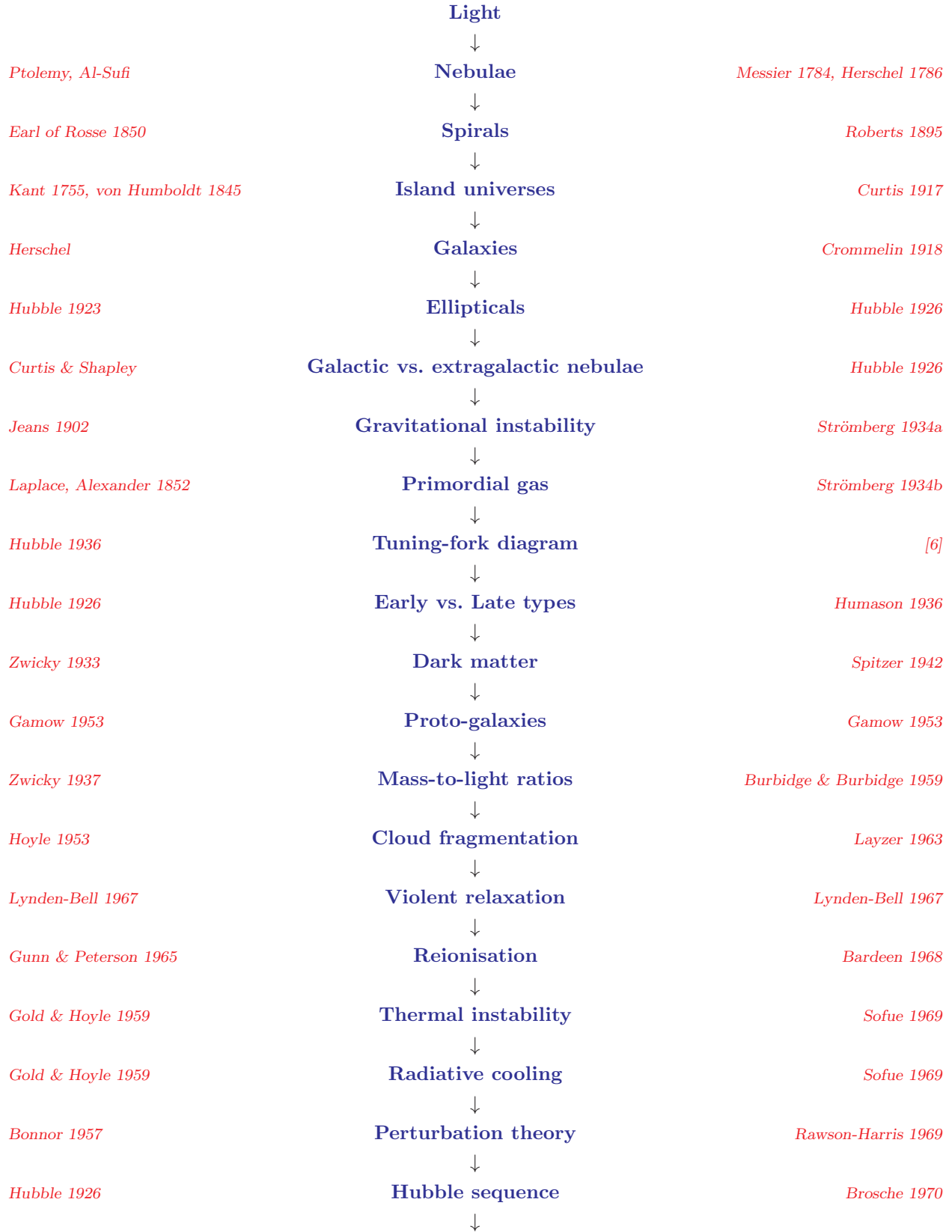
## The story so far

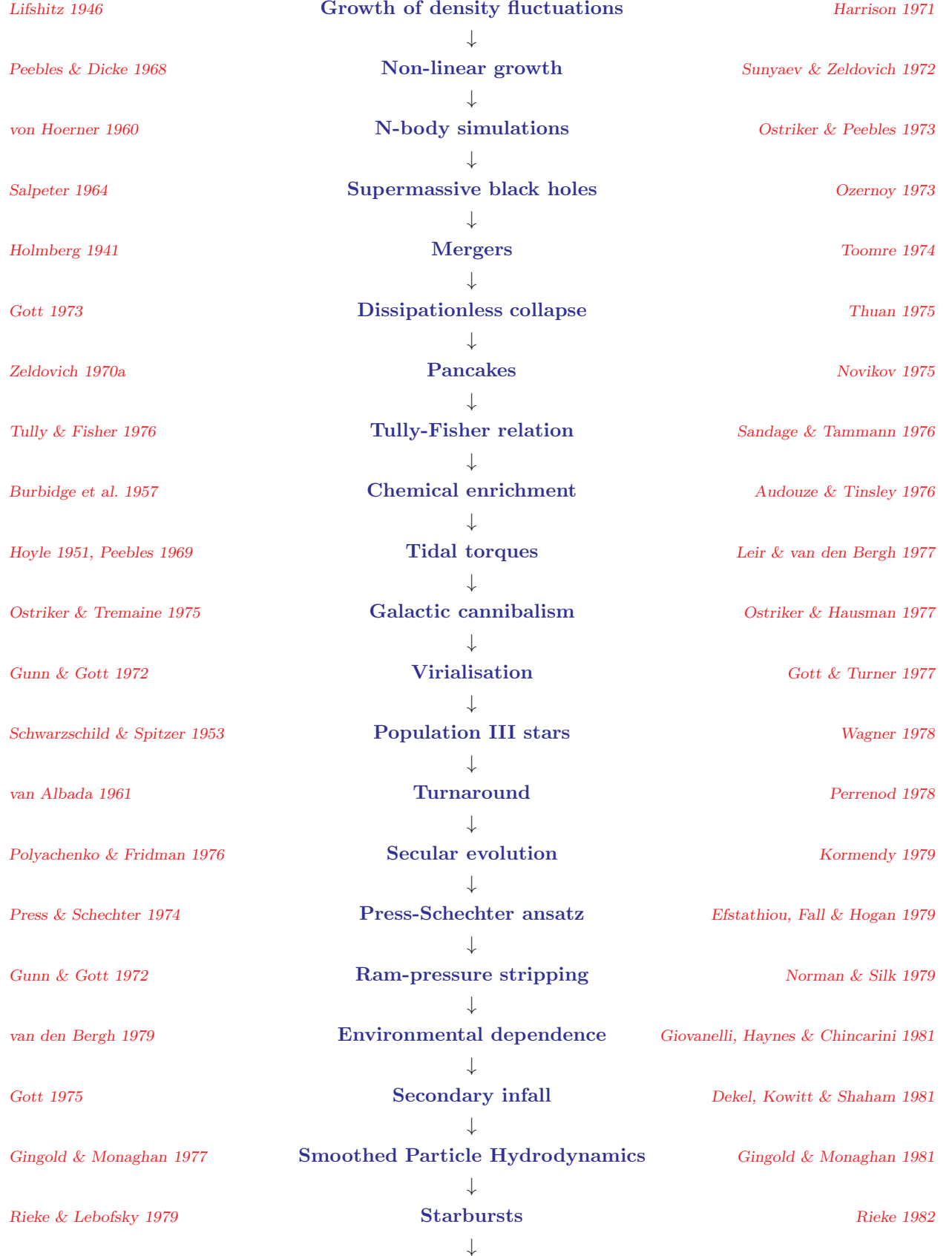
Galaxy formation is a complex subject, and the fundamental question “how do galaxies form?” is poorly defined. Galaxies do not “form” instantaneously, and there is no sharp dividing line between their creation and the evolution of their properties. Understanding how lumps of a specific size developed from simplicity to complexity is clearly a challenging endeavour. Different researchers approach this from a variety of directions, and the history of progress on this topic is replete with ideas that have temporarily captured the imagination of astrophysicists. This history can be followed through a series of the most important review (or review-like) articles, including Gamow (1948), Hoyle (1953), Sciama (1955), Eggen, Lyden-Bell & Sandage (1962), Layzer (1964), Peebles (1965), Doroshkevich, Zeldovich & Novikov (1967), Larson (1969), Harrison (1970), Peebles (1974), Jones (1976), Gott (1977), Rees (1978), Efstathiou & Silk (1983), Blumenthal et al. (1984), White (1995), Baugh (2006) and Benson (2010), as well as books by Longair (1998, 2008), Spinrad (2005) and Mo, Van den Bosch & White (2010).

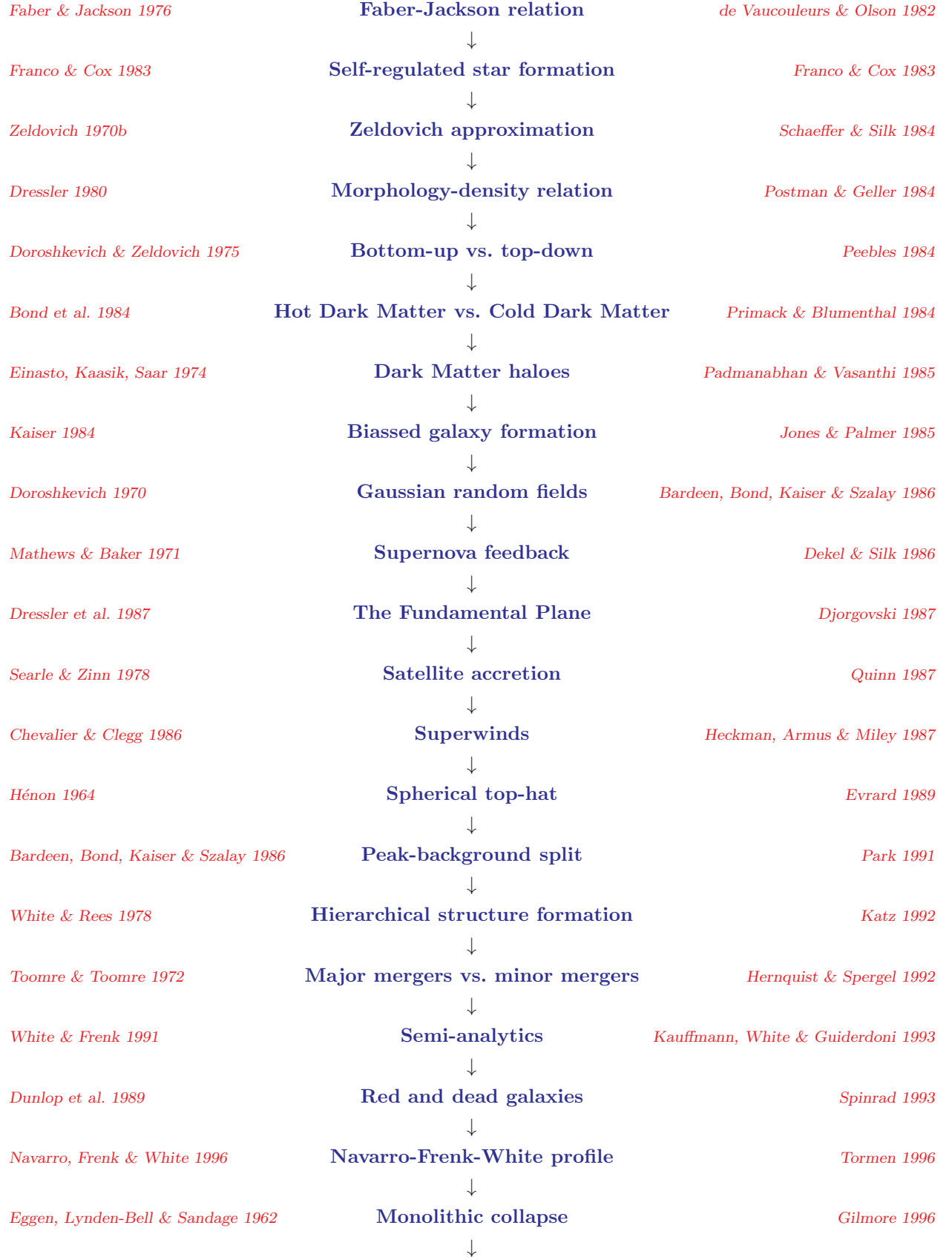
However, instead of reviewing these reviews, I present a brief timeline for the development of the concepts underlying our current understanding of galaxy formation [1]. This is best told via pieces of what was once called “rhetorick” and in the modern age might be known as “catchphrases”, “sound-bites” or “spin” [2]. For each of these physical ideas, I have tried to identify the originator as well as when the idea caught on, as traced through the first paper found with the relevant phrase in the title or abstract [3]. These entries are arranged in chronological order of first appearance of each phrase, which in some cases may be a surprisingly long time after the concept was first described. No attempt has been made to measure how prevalent each idea has been, or to track its rise and fall [4]. Imperfect as it may be, this list provides an interesting history of ideas in this perplexing branch of astrophysics [5].

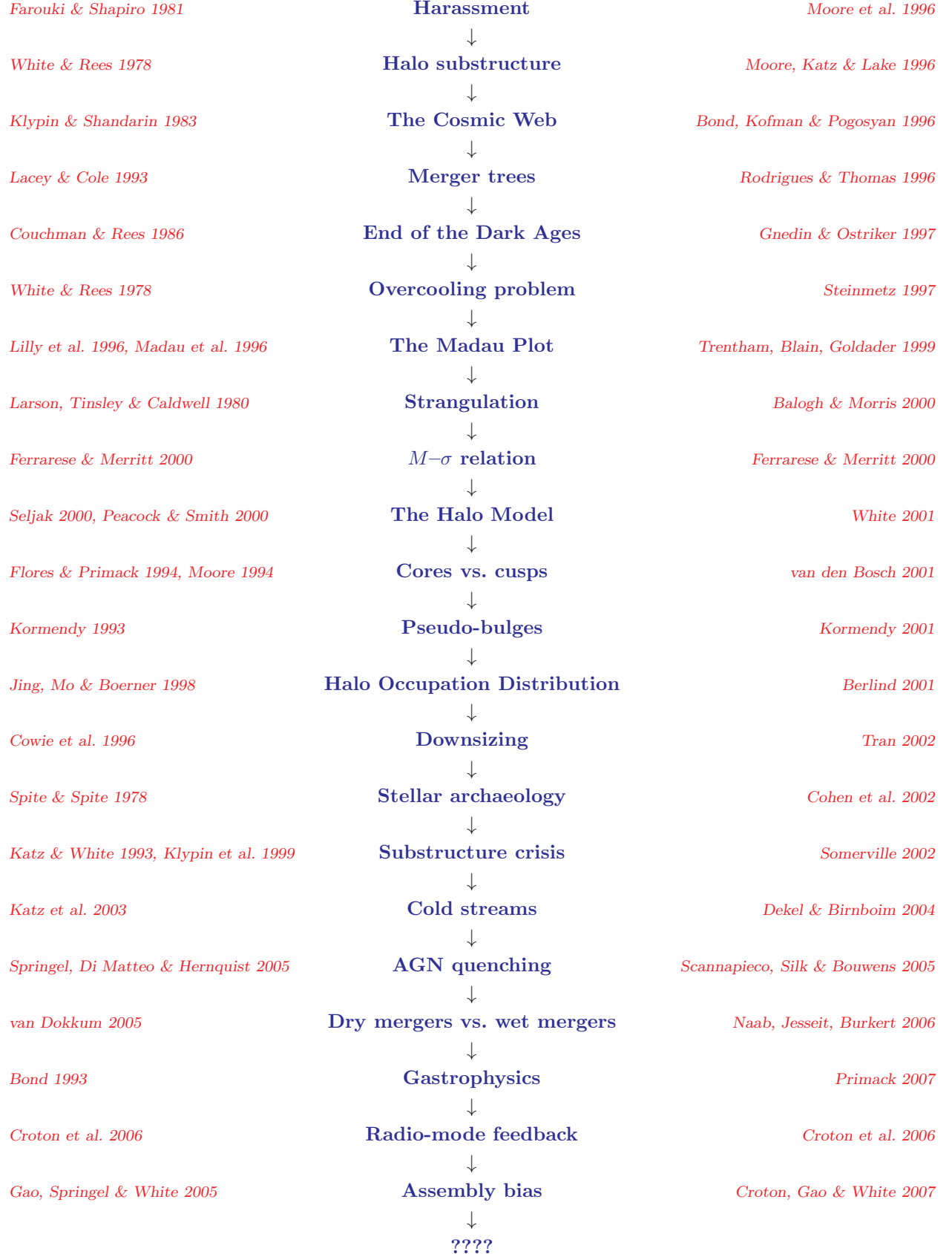
# ORIGIN

# USAGE









## Lessons

What can we learn from this timeline by viewing it as a process? First, if we simply count ideas, and assume there is a bandwagon effect associated with each one, then the duration of each fad is approximately one year [7]. The corollary to this finding, and the advice for new researchers, is that one should jump quickly onto bandwagons before they pass. The second point is that not all of the concepts listed are entirely new, and it may even seem to the cynical reader that some apparently new suggestions are simply recycled from earlier ones, but with new names. This leads to another recommendation for those who wish to make an impact on galaxy formation – study what is already known, find something that has not been highlighted much before, and come up with a new name for it.

## Sidelines

We end with a list of ideas that are at least a little off the mainstream of galaxy formation research. These are the “also-ran” or “dead-end” concepts, some of which seemed a bit outré in the first place, while others appeared promising briefly, but were ultimately seen to be merely a distraction [8]. Such ideas might include: primordial turbulence; continuous creation; cosmic explosions; mock gravity; isocurvature baryons; cosmic string wakes; textures; late time phase transitions; warm dark matter; self-interacting dark matter; cooling flows; hyper-extended perturbation theory; retarded galaxies in voids; jet-triggered star formation; fractal structure; plasma cosmology; MOND; MOG; primordial black holes; primordial magnetic fields; etc.

No doubt there will be many more such notions to come. Only time will tell whether any of them become part of the main narrative.

## The future

Experts disagree on whether we are about to enter a golden “precision era” of galaxy formation or whether the subject is essentially over, with just the weather-prediction details left to fuss about. Although precise future directions are unknown, some general predictions are possible: (1) galaxy formation will not be completely “solved” in the near future; (2) ambitious multi-wavelength surveys will extend our empirical understanding of the high- $z$  Universe; (3) there will continue to be phrases spun to describe new ideas; (4) some of these ideas will be old ideas, dressed up; (5) some ideas will be crazy, and will fall by the wayside; but (6) some ideas will genuinely progress the field, inspiring a new generation of galaxy fabricators.

## Notes and references

- [1] The boundaries are of course quite blurred between galaxy formation and the nearby topics of star formation, cluster physics and large-scale structure. The choice of how far to explore around these boundaries is necessarily quite subjective.
- [2] Using analogies from the world’s of entertainment, the media and politics. The web 2.0 version would be “meme”.
- [3] For tracking down the source of a phrase or idea, I have tried to simplify a complicated history by picking a single paper in most cases. There will undoubtedly be errors in this process, and I apologise for either getting the originator wrong, or missing an earlier example of the use of the phrase. The main aim of the “usage” column is to trace when the idea started to become popular in the literature, and to be definitive I focus on abstracts of papers in journals or conference proceedings, ignoring AAS abstracts or telescope proposals.
- [4] One could study the longevity of each idea, and whether specific periods of time, scientists or journals have been more productive, etc. This is complicated by the fact that some phrases were originally coined with a slightly different meaning, e.g. “starburst” (the nucleus only), “quenching” (of radio emission) and “cold streams” (tidal debris). Tracking the citations is made more difficult as a result of the natural tendency of researchers to consider history to have started when they entered the field. Because of these complications I leave it to more serious historians of science to trace the detailed evolution of each idea. My colleague Dr. Frolop has already embarked on such a project.

- [5] Other areas of astrophysics could surely be traced in a similar way; however, galaxy formation seems to have more than its fair share of these catchphrases, presumably because it is a complex subject, which has to be tackled from many different perspectives.
- [6] This term is often used in popular-level presentations, but rarely in technical papers.
- [7] Many ideas are current at the same time of course, so this estimate is really the new bandwagon rate. Catchphrases differ in their longevity, some taking a long time to be picked up in the literature after first being discussed, while others resonating instantly with other researchers.
- [8] Although of course no idea ever dies entirely.
- [9] This article made use of NASA's Astrophysical Data System Bibliographic Services. I wish to acknowledge discussions with and advice from many colleagues, particularly those who refrained from simply pointing out which ideas had been theirs.

Alexander S., 1852, *AJ*, 2, 36  
 Audouze J., Tinsley B.M., 1976, *ARAA*, 14, 43  
 Balogh M.L., Morris S.L., 2000, *MNRAS*, 318, 703  
 Bardeen J.M., 1968, *AJ*, 73, 164  
 Bardeen J.M., Bond J.R., Kaiser N., Szalay A.S., 1986, *ApJ*, 304, 15  
 Baugh C.M., 2006, *Rept. Prog. Phys.*, 69, 3101  
 Benson A.J., 2010, *Phys. Rep.*, 495, 33  
 Berlind A.A., 2001, Ph.D. thesis, Ohio State University  
 Blumenthal G.R., Faber S.M., Primack J.R., Rees M.J., 1984, *Nature*, 311, 517  
 Bond J.R., Centrella J., Szalay A.S., Wilson J.R., 1984, in "Formation and evolution of galaxies and large structures in the universe, 3rd Moriond Astrophysics Meeting", Reidel, Dordrecht, p. 87  
 Bond J.R., Kofman L., Pogosyan D., 1996, *Nature*, 380, 603  
 Bond J.R., 1993, in "The environment and evolution of galaxies, 3rd Tetons summer school", ed. J.M. Shull, H.A. Thronson, Kluwer, Dordrecht, p. 3  
 Bonnor W.B., 1957, *MNRAS*, 117, 104  
 Brosche P., 1970, *A&A*, 6, 240  
 Burbidge G.R., Burbidge E.M., 1959, *ApJ*, 130, 15  
 Burbidge E.M., Burbidge G.R., Fowler W.A., Hoyle F., 1957, *Rev. Mod. Phys.*, 29, 547  
 Chevalier R.A., Clegg A.W., 1986, *Nature*, 317, 44  
 Cohen J.G., et al., 2002, *AJ*, 124, 470  
 Couchman H.M.P., Rees M.J., 1986, *MNRAS*, 221, 53  
 Cowie L.L., Songaila A., Hu E., Cohen J.G., 1996, *AJ*, 112, 839  
 Croton D.J., et al., 2006, *MNRAS*, 365, 11  
 Croton D.J., Gao L., White S.D.M., 2007, *MNRAS*, 374, 1303  
 Crommelin A.C.D., 1918, *JRASC*, 12, 33  
 Curtis H.D., 1917, *PASP*, 29, 206  
 Dekel A., Birnboim Y., 2004, in "The new cosmology: conference on strings and cosmology", AIP Conf. Proc., Vol. 743, p. 162  
 Dekel A., Kowitt M., Shaham J., 1981, *ApJ*, 250, 561  
 Dekel A., Silk J., 1986, *ApJ*, 303, 39  
 de Vaucouleurs G., Olson D.W., 1982, *ApJ*, 256, 346  
 Djorgovski S., 1987, in "Structure and dynamics of elliptical galaxies", Reidel, Dordrecht, p. 79  
 Doroshkevich A.G., 1970, *Astrophysica*, 6, 320  
 Doroshkevich A.G., Zeldovich Ya.B., 1975, *Ap&SS*, 35, 55  
 Doroshkevich A.G., Zeldovich Ya.B., Novikov I.D., 1967, *Sov. Astron.*, 11, 233  
 Dressler A., 1980, *ApJ*, 236, 351  
 Dressler A., Lynden-Bell D., Burstein D., Davies R.L., Faber S.M., Terlevich R.J., Wegner G., 1987, *ApJ*, 313, 42  
 Dunlop J.S., Guiderdoni B., Rocca-Volmerange B., Peacock J.A., Longair M.S., 1989, *MNRAS*, 240, 257  
 Earl of Rosse, 1850, *Phil. Trans. Royal Soc.*, 140, 499  
 Efsthathiou G., Fall S.M., Hogan C., 1979, *MNRAS*, 189, 203  
 Efsthathiou G., Silk J., 1983, *Fund. Cosm. Phys.*, 9, 1  
 Eggen O.J., Lyden-Bell D., Sandage A.R., 1962, *ApJ*, 136, 748  
 Einasto J., Kaasik A., Saar E., 1974, *Nature*, 250, 309

Evrard A.E., 1989, ApJ, 341, 26  
 Faber S.M., Jackson R.E., 1976, ApJ, 204, 668  
 Farouki R., Shapiro S.L., 1981, ApJ, 243, 32  
 Ferrarese L., Merritt D., 2000, ApJ, 539, L9  
 Flores R.A., Primack J.R., 1994, ApJ, 427, L1  
 Franco J., Cox D.P., 1983, ApJ, 273, 243  
 Gamow 1948, Phys. Rev., 74, 505  
 Gamow 1953, AJ, 58, 39  
 Gao L., Springel V., White S.D.M., 2005, MNRAS, 363, L66  
 Gilmore G., 1996, ASP Conf. Ser., Vol. 92, p. 161  
 Gingold R.A., Monaghan J.J., 1977, MNRAS, 181, 375  
 Gingold R.A., Monaghan J.J., 1981, MNRAS, 197, 461  
 Giovanelli R., Haynes M.P., Chincarini G.L., 1981, ApJ, 247, 383  
 Gnedin N.Y., Ostriker J.P., 1997, ApJ, 486, 581  
 Gold T., Hoyle F., 1959, in “Paris Symposium on Radio Astronomy”, ed. R.M. Bracewell, Stanford University Press, Palo Alto, p. 583  
 Gott J.R., 1973, ApJ, 186, 481  
 Gott J.R., 1975, ApJ, 201, 296  
 Gott J.R., 1977, ARA&A, 15, 235  
 Gott J.R., Turner E.L., 1977, ApJ, 213, 309  
 Gunn J.E., Gott J.R. 1972, ApJ, 176, 1  
 Gunn J.E., Peterson B.A., 1965, ApJ, 142, 1633  
 Harrison E.R., 1970, MNRAS, 148, 119  
 Harrison E.R., 1971, MNRAS, 154, 167  
 Heckman T.M., Armus L., Miley G.K., 1987, AJ, 93, 276  
 Hénou M., 1964, Ann. d’Astrophys., 27, 83  
 Hernquist L., Spergel D.N., 1992, ApJ, 399, L117  
 Herschel W., 1786, Phil. Trans. R. Soc. London, 76, 457  
 Holmberg E., 1941, ApJ, 94, 385  
 Hoyle F., 1951, in “Problems of Cosmical Aerodynamics”, Central Air Documents Office, Dayton, Ohio, p. 195  
 Hoyle F., 1953, ApJ, 118, 513  
 Hubble E.P., 1923, Popular Astron., 31, 644  
 Hubble E.P., 1926, ApJ, 64, 321  
 Hubble E.P., 1936, “The Realm of the Nebulae”, Yale University Press, New Haven  
 Humason M.L., 1936, ApJ, 83, 10  
 Jeans J.H., 1902, Phil. Trans. R. Soc. London A, 199, 1  
 Jing Y.P., Mo H.J., Boerner G., 1998, ApJ, 494, 1  
 Jones B.J.T., 1976, Rev. Mod. Phys., 48, 107  
 Jones B.J.T., Palmer P.L., 1985, in ‘Galaxies, axisymmetric systems and relativity’, Cambridge University Press, Cambridge, p. 3  
 Kaiser N., 1984, ApJ, 284, L9  
 Kant I., 1755, Allgemeine Naturgeschichte und Theorie des Himmels, Johann Friedrich Petersen, Königsberg and Leipzig  
 Katz N., 1992, PASP, 104, 852  
 Katz N., Kereš D., Davé R., Weinberg D.H., 2003, in “The IGM/galaxy connection”, ASSL Conf. Proc., Vol. 281, Kluwer, Dordrecht, p. 185  
 Katz N., White S.D.M., 1993, ApJ, 412, 455  
 Kauffmann G., White S.D.M., Guiderdoni B., 1993, MNRAS, 264, 201  
 Klypin A.A., Kravtsov A.V., Valenzuela O., Prada F., 1999, ApJ, 522, 82  
 Klypin A.A., Shandarin S.F., 1983, MNRAS, 204, 891  
 Kormendy J., 1979, ApJ, 227, 714  
 Kormendy J., 1993, in “Galactic Bulges”, IAU Symp. 153, ed. H. Dejonghe, H.J. Habing, Kluwer, Dordrecht, p. 209  
 Kormendy J., 2001, in “Galaxy Disks and Disk Galaxies”, ASP Conf. Ser., Vol. 230, p. 247  
 Lacey C., Cole S., 1993, MNRAS, 262, 627



Larson R.B., 1969, MNRAS, 145, 405  
 Larson R.B., Tinsley B.M., Caldwell C.N., 1980, ApJ, 237, 692  
 Layzer D., 1963, ApJ, 137, 351  
 Layzer D., 1964, ARA&A, 2, 341  
 Leir A.A., van den Bergh S., 1977, ApJS, 34, 381  
 Lifshitz E.M., 1946, J. Phys. U.S.S.R., 10, 110  
 Lilly S.J., Le Fevre O., Hammer F., Crampton D., 1996, ApJ, 460, L1  
 Longair M.S., 1998, 2008, "Galaxy formation", Springer-Verlag, Berlin  
 Lynden-Bell D., 1967, MNRAS, 136, 101  
 Madau P., Ferguson H.C., Dickinson M.E., Giavalisco M., Steidel C.C., Fruchter A., 1996, MNRAS, 283, 1388  
 Mathews W.G., Baker J.C., 1971, ApJ, 170, 241  
 Messier C., 1781, Connaissance des Temps, pp. 227–267 (published in 1784)  
 Mo H., Van den Bosch F., White S.D.M., 2010, "Galaxy Formation and Evolution", Cambridge University Press, Cambridge  
 Moore B., 1994, Nature, 370, 629  
 Moore B., Katz N., Lake G., 1996, ApJ, 457, 455  
 Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, Nature, 379, 613  
 Naab T., Jesseit R., Burkert A., 2006, MNRAS, 372, 839  
 Navarro J.F., Frank C.S., White S.D.M., 1996, ApJ, 462, 563  
 Norman C., Silk J., 1979, ApJ, 233, L1  
 Novikov I.D., 1975, AZh, 52, 1038  
 Ostriker J.P., Hausman M.A., 1977, ApJ, 217, L125  
 Ostriker J.P., Peebles, 1973, ApJ, 186, 467  
 Ostriker J.P., Tremaine S., 1975, ApJ, 202, L113  
 Ozernoy L.M., 1973, Astron. Tsirk, 804, 1  
 Padmanabhan T., Vasanthi M.M., 1985, JApA, 6, 261  
 Park C., 1991, MNRAS, 251, 167  
 Peacock J.A., Smith R.E., 2000, MNRAS, 318, 1144  
 Peebles P.J.E., 1965, ApJ, 142, 1317  
 Peebles P.J.E., 1969, ApJ, 155, 393  
 Peebles P.J.E., 1974, I.A.U. Symp., 58, 55  
 Peebles P.J.E., 1984, in 'Clusters and groups of galaxies', ed. F. Mardirossian et al., Reidel, Dordrecht, p. 405  
 Peebles P.J.E., Dicke R.H., 1968, ApJ, 154, 891  
 Perrenod S.C., 1978, ApJ, 224, 285  
 Polyachenko V.L., Fridman A.M., 1976, "Equilibrium and stability of gravitating systems", Nauka, Moscow  
 Postman M., Geller M.J., 1984, ApJ, 282, 95  
 Press W.H., Schechter P., 1974, ApJ, 187, 425  
 Primack J.R., 2007, Nucl. Phys. B Supp., 173, 1  
 Primack J.R., Blumenthal G.R., 1984, in "Formation and evolution of galaxies and large structures in the universe, 3rd Moriond Astrophysics Meeting", Reidel, Dordrecht, p. 163  
 Quinn P.J., in "Nearly normal galaxies: From the Planck time to the present", ed. S.M. Faber, Springer-Verlag, New York, p. 138  
 Rawson-Harris D., 1969, MNRAS, 143, 49  
 Rees M.J., 1978, in "Observational cosmology, 8th Saas-Fee Advanced Course", Sauveny, Geneva Observatory, p. 259  
 Rieke G.H., 1982, in "Extragalactic radio sources", Reidel, Dordrecht, p. 239  
 Rieke G.H., Lebofsky M.J., 1979, ARAA, 17, 477  
 Roberts I., 1895, MNRAS, 56, 70  
 Rodrigues D.D.C., Thomas P.A., 1996, in "Formation of the Galactic Halo ... Inside and Out", ASP Conf. Ser., Vol. 92, p. 505  
 Salpeter E.E., 1964, ApJ, 140, 796  
 Sandage A., Tammann G.A., 1976, ApJ, 210, 7  
 Scannapieco E., Silk J., Bouwens R., 2005, ApJ, 635, L13  
 Schaeffer R., Silk J., 1984, A&A, 130, 131  
 Schwarzschild M., Spitzer L., 1953, Obs., 73, 77

Sciamia D.W., 1955, MNRAS, 115, 3  
 Searle L., Zinn R., 1978, ApJ, 225, 357  
 Seljak U., 2000, MNRAS, 318, 203  
 Sofue Y., 1969, PASJ, 21, 211  
 Somerville R.S., 2002, ApJ, 572, L23  
 Spinrad H., 1993, in “The environment and evolution of galaxies, 3rd Tetons summer school”, ed. J.M. Shull, H.A. Thronson, Kluwer, Dordrecht, p. 151  
 Spinrad H., 2005, “Galaxy Formation and Evolution”, Springer-Verlag, Berlin  
 Spite F., Spite M., 1978, A&A, 67, 23  
 Spitzer L., 1942, ApJ, 95, 329  
 Springel V., Di Matteo T., Hernquist L., 2005, ApJ, 620, L79  
 Steinmetz M., 1997, in “The Early Universe with the VLT”, ed. J. Bergeron, Springer, Berlin, p. 156  
 Strömberg G., 1934a, ApJ, 79, 460  
 Strömberg G., 1934b, ApJ, 80, 327  
 Sunyaev R.A., Zeldovich Ya.B., 1972, A&A, 20, 189  
 Thuan T.X., 1975, Nature, 257, 774  
 Toomre A., 1974, I.A.U. Symp., 58, 347  
 Toomre A., Toomre J., 1972, ApJ, 178, 623  
 Tormen G., 1996, in “Mapping, measuring, and modelling the universe”, ASP Conf. Ser., Vol. 94, p. 131  
 Tran K.-V.H., 2002, Ph.D. thesis, U.C. Santa Cruz  
 Trentham N., Blain A.W., Goldader J., 1999, MNRAS, 305, 61  
 Tully R.B., Fisher J.R., 1976, A&A, 54, 661  
 van Albada G.B., 1961, AJ, 66, 590  
 van den Bergh S., 1979, Astron. Nachr., 300, 225  
 van den Bosch F.C., Swaters R.A., 2001, MNRAS, 325, 1017  
 van Dokkum P.G., 2005, AJ, 130, 2647  
 von Hoerner S., 1960, Zeit. für Astrophysik, 50, 184  
 von Humboldt, 1845, “Kosmos”, Vol. I, Hippolyte Baillière, London  
 Wagner R.L., 1978, A&A, 62, 9  
 White M., 2001, MNRAS, 321, 1  
 White S.D.M., 1995, in “1993 Les Houches Lectures on Large-Scale Structure”, ed. R. Schaeffer, Elsevier, Netherlands  
 White S.D.M., Frenk C., 1991, ApJ, 457, 645  
 White S.D.M., Rees M.J., 1978, MNRAS, 183, 341  
 Zeldovich Ya.B., 1970a, Astrofizika, 6, 319  
 Zeldovich Ya.B., 1970b, A&A, 5, 84  
 Zwicky F., 1933, Helv. Phys. Acta, 6, 110  
 Zwicky F., 1937, ApJ, 86, 217